Progress report on AOARD contract FA2386-09-1-4132, "Laser stabilization for Doppler lidar of the ionosphere"

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The goal of this contract is to improve remote monitoring of ionospheric conditions by enabling velocity-resolving lidar of the N_2^+ molecule. The forecasting of space weather, in particular the condition of the ionosphere, is crucial to the reliability of long-distance radio and satellite communications, and is already the target of significant efforts by the Air Force. Monitoring N_2^+ concentration and velocity would provide crucial data for modeling and forecasting ionospheric conditions.

Doppler lidar is a well-known laser technique for resolving the velocity of molecules by remote sensing, but requires highly accurate frequency stabilization of the laser source near an optical transition of the relevant molecular species. Typically, the velocity distribution of molecules in ionospheric conditions leads to Doppler shifts of optical transitions on the order of 1 GHz, so the lidar laser source should be reliably frequency-tunable in steps of >100 MHz near the transition frequency in order to resolve the Doppler profile of the ionospheric molecules. This requirement is reliably and robustly satisfied by performing spectroscopy on a local sample of the relevant molecular species to obtain a reference signal related to the laser frequency. The laser is then feedback-stabilized to the desired frequency and can be tuned either by adjusting the reference signal or by external frequency shifting.

Until recently, no such spectroscopic frequency references have been available for atomic or molecular ions. In 2008 we demonstrated the first absolute frequency referencing of a laser to atomic ions in a discharge lamp [SK08]. The reference was found to have stability of 350 kHz over a few seconds and 20 MHz over a period of a week under laboratory conditions. For this contract, we proposed to construct a discharge-based frequency reference for N_2^+ suitable for field deployment in a lidar system.

Molecular frequency stabilization systems are highly wavelength-specific. The construction of the N_2^+ frequency reference therefore relies critically on wavelength data from lidar surveys, which is to be obtained by our collaborators at University of Alaska. The surveys have so far been unsuccessful in determining the optimum wavelength for N_2^+ lidar, ultimately owing to problems with the high-power dye laser system used as the lidar source [Co11]. However, PI Kielpinski was able to remotely diagnose problems with the dye laser system and suggest improvements that resulted in a 50% increase in power. Since lidar systems are generally critically limited by the source power, we are optimistic that a future survey will enable definite determination of the optimal lidar wavelength. A no-cost extension to the contract period was requested and granted on this basis.

In this period we measured the long-term frequency stability of the Yb^+ reference to be better than 100 MHz over a full year, using laser-cooled, trapped Yb^+ ions in our laboratory as a calibration standard. The ion trapping apparatus is quite delicate, so calibration of the reference cannot be performed in the field. This stability measurement shows that a Doppler lidar system using our reference can achieve high velocity resolution during a field deployment of at least one year.

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The Yb^+ reference has proved to be robust against changes of the discharge source and the magnetic field used for our spectroscopy technique. At one point over the past year, we replaced the discharge lamp with a new model from a different manufacturer. The new lamp geometry forced us to reconfigure the permanent magnets, changing the magnetic field at the discharge by tens of Gauss. We calibrated the reference against laser-cooled Yb^+ ions before and after the change in apparatus and observed a frequency shift of less than 100 MHz. Hence, the components of the reference can be replaced and even substantially altered in the field, while maintaining the calibration needed for high-resolution Doppler lidar.

We have also investigated the use of other spectroscopic techniques based on the optogalvanic effect as a source for the frequency reference signal [PK09]. Optogalvanic techniques remove the need for polarization control of the laser and optical detection of the signal, reducing the cost and improving the robustness of the reference. As shown in Fig. 1, we were able to obtain a high-quality optogalvanic signal on the 638 nm ${}^2F_{7/2} - {}^1D[5/2]_{5/2}$ transition of Yb^+ ions in a discharge lamp. The signal-to-noise of the optogalvanic technique is at least 100:1 over the observed linewidth of 1.9 GHz (FWHM). With somewhat more care, 100 MHz stability should be readily achievable in this system.

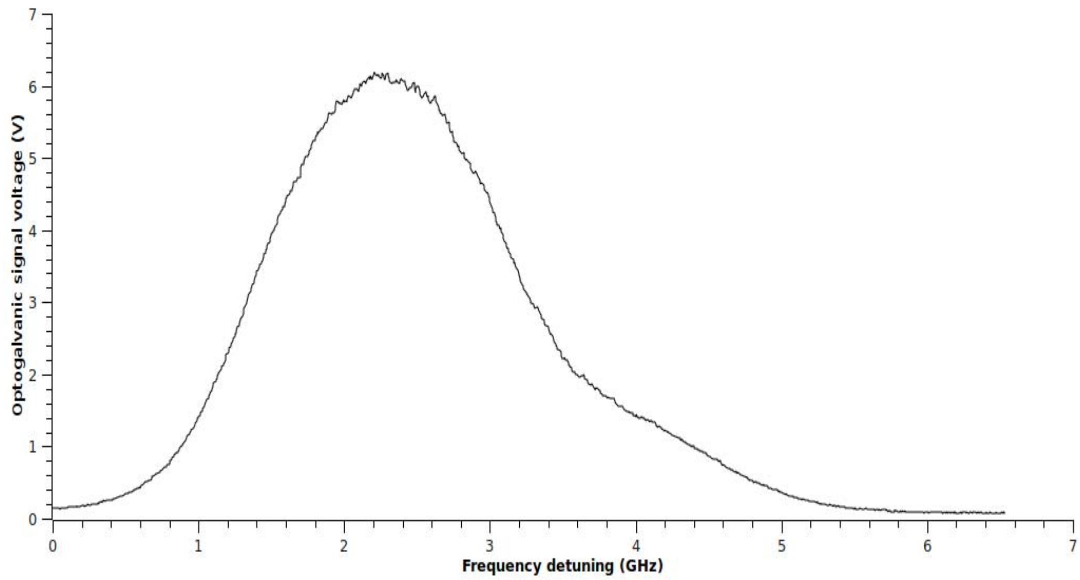

Figure 1. Optogalvanic signal acquired at the 638 nm transition of Yb^+ ions in a discharge lamp.

Ion densities in typical discharge lamps are relatively low, limiting the spectroscopic signal obtainable from these references. Ion production in a discharge arises from complex, nonequilibrium collisional processes, specific to the ionic species of interest and the buffer gas employed as the discharge medium. It is therefore difficult to predict optimal discharge parameters for maximum ion density. We used both emission spectroscopy and optogalvanic spectroscopy to investigate ion production in several Yb^+ discharge lamps with various geometries and buffer-gas species as a function of electrical drive power and buffer-gas pressure. Both Ar and Ne buffer gases were found to generate Yb^+ ions, but only Ne buffer gas populated the lower level of the 638 nm transition. In every case, ion generation relied on drive current at least 10× higher than needed for generation of neutral Yb atoms from the Yb cathode of the lamp. Narrowing of the transition linewidth to 1.5 GHz was observed as the buffer-gas pressure was

decreased from 5 torr to 500 mtorr, but the ion density decreased more rapidly than the linewidth, so the higher pressure is more favorable for signal-to-noise of the frequency reference.

In the next period, we hope to obtain the key wavelength data from our collaborators that will enable us to construct an appropriate N_2^+ discharge lamp and a frequency reference based on this lamp. Depending on the timeline, this reference may be integrated in the Alaska laser system for the next N_2^+ lidar survey in late 2011. We will continue our efforts to characterize the Yb^+ reference using our trapped-ion calibration standard and investigate the effects of discharge parameters on the stability and reliability of the reference.

References

[Co11] R.L. Collins, private communication (2011).
[SK08] E.W. Streed, T.J. Weinhold, and D. Kielpinski, *Appl Phys Lett* **93**, 071103 (2008).

Publications relating to this contract:

[PK09] “Optogalvanic spectroscopy of the $^2F_{7/2}$ – $^1D[5/2]_{5/2}$ repumper transition for Yb^+ optical frequency standards,” MJ Petrasiunas, EW Streed, TJ Weinhold, BG Norton, WM Itano, and D Kielpinski, Proceedings of the Australasian Conference on Optics, Lasers, and Spectroscopy 2009